(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 August 2003 (28.08.2003)

PCT

(10) International Publication Number
WO 03/070414 A1

(51) International Patent Classification[7]: **B23K 26/03**, 26/34, F01D 5/00, 5/28

(21) International Application Number: PCT/CH03/00098

(22) International Filing Date: 10 February 2003 (10.02.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
02405126.0 20 February 2002 (20.02.2002) EP

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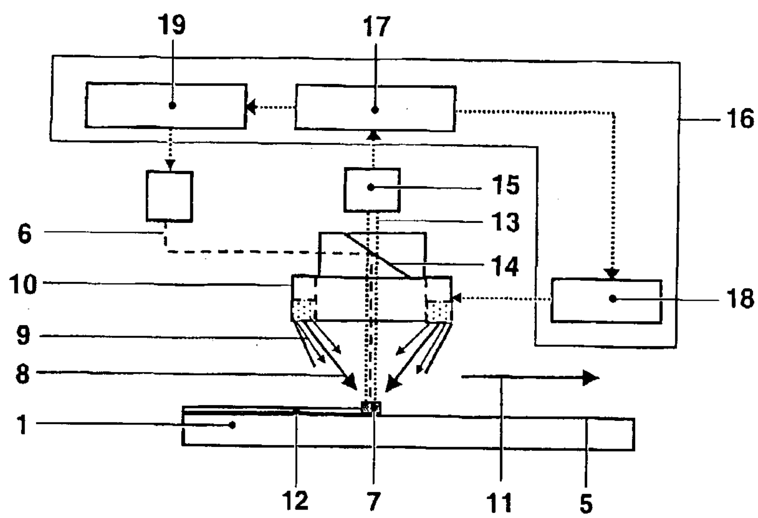
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

[Continued on next page]

(54) Title: METHOD OF CONTROLLED REMELTING OF OR LASER METAL FORMING ON THE SURFACE OF AN ARTICLE



(57) Abstract: It is disclosed a method for controlled remelting of or laser metal forming on the surface (5) of an article (1). A light source and a signal capturing apparatus (15) is moved over the article (1). The light source with a specific power is used to melt the surface (5) of the article (1) locally and to form a melt pool (7). Thereby an optical signal (13) is captured by the signal capturing apparatus from the melt pool (7), and the monitored optical signal (13) is used for the determination of temperature and temperature fluctuations as properties of the melt pool (7). Furthermore, a control system (16) with a feedback circuit is used to adjust at least one process parameter such as the power of the light source such that desired melt pool properties are obtained. Subsequently the melt pool (7) solidifies.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

Method of controlled remelting of or laser metal forming on the surface of an article

FIELD OF THE INVENTION

The invention relates to a method of controlled remelting of or laser metal forming on the surface of articles according to the claim 1 and 2.

BACKGROUND OF THE INVENTION

In the last years laser metal forming (LMF) has been introduced in industrial manufacturing. Laser metal forming is a process where a high power laser locally melts a focussed stream of metal powder or a metal wire onto a substrate. In this way material can be added to the underlying part. The method is suitable for controlled material build-up and the laser generated parts are characterised by a dense microstructure which is usually free of pores.

Laser metal forming has been recently used for commercial manufacturing of superalloys due to its attractive potential for repair of locally damaged or worn parts. Indeed, it is possible to selectively add material at desired locations and

to re-establish the full functionality of a component. It is clear that laser repair technology is particularly attractive for the refurbishment of expensive parts that are affected by local damage or local mechanical wear. Turbine blades and vanes are typical examples. However, the process is complicated when single-crystal components have to be refurbished. Single crystal blades and vanes can be found in the most heavily loaded rows of modern gas turbines (first or high pressure row). Their mechanical integrity relies on the particular properties due to single-crystal microstructure and the absence of grain boundaries. Reconditioning of such components is only feasible if the single crystal microstructure can be maintained during the repair process.

During laser metal forming substrate material is locally molten and powder (or wire) is injected into the melt pool with a suitable powder (or wire) feeder mechanism . After a certain interaction time (which is determined by the laser spot size and the relative movement between laser and substrate) the molten material resolidifies leading to material build-up on the substrate.

However, during the solidification of the molten material new grains may form in the melt pool due to constitutional undercooling of the liquid melt. The growth of these newly formed grains leads to undesired build-up of equiaxed material, i.e. material that is oriented in a random manner. As the thermomechanical properties of superalloys greatly depend on the crystallographic orientation and as SX crystal components rely on the benefit of preferable orientation it is obvious that the consequence of equiaxed growth is a serious degradation of the mechanical properties. Moreover, superalloys which do not contain grain boundary stabilizing elements exhibit excessive creep when unwanted grain boundaries are formed. For epitaxial laser metal forming it is therefore crucial to ensure a completely SX microstructure of a part by avoiding the so-called columnar to equiaxed transition (CET).

One strategy for ensuring epitaxial growth, i.e. growth with orientation matched to the substrate and without formation of new grains, is to use special process conditions. Laser parameters have to be adjusted in a manner

that a specific ratio between temperature gradient G and the solidification speed V_s is maintained. Both quantities depend not only on laser parameters such as power, power density, advance speed but also on the properties of the substrate and powder (or wire) material.

Those skilled in the art of laser metal forming are also aware that the onset of (marangoni) convection in the melt pool is one of the main reasons for the undesired CET. Initiation of convection processes in the melt pool leads to fragmentation of the fragile dendrites that form during the solidification of the molten material. By the effect of convective transport dendrite fragments are distributed all over the melt pool where they acts as nucleation sites and promote the formation of equiaxed material. Unfortunately melt pool convection is also affected by other process parameters like mass feed rate, protection gas stream, injection angle. In addition, marangoni convection is not readily detectable without melt pool monitoring.

So far, several patents have been issued for the laser metal forming process. The basic principle is described in EP-A1-0 558 870, DE-C1-199 49 972, US-A-5,873,960, US-A-5,622,638 or US-A-4,323,756.

The application of epitaxial material build-up for protective coatings is covered by US-A-6,277,500, applications for generation or refurbishment of single crystal components are described in US-A-6,024,792, EP-A1-0 740 977, WO95/35396 or US-A-5,914,059. Except US-A-6,024,792 none of these patents mentions the significance of the G, V_s parameters in order to obtain the desired single crystal microstructure. US-A-6,024,792 states that the laser power has to be set in a way to obtain adequate values for G and V_s, however, does not suggest a method for automatic laser power control or for avoiding melt pool convections.

Another patent application, WO95/06540 suggests the use of a pyrometer for interactive laser welding of super alloy articles measuring the substrate preheating temperature.

The collection of optical signals from the melt pool is also depicted in US-A-6,122,564. In this patent, an optical monitoring system is connected to a feed-back controller in order to adjust the material deposition rate depending on the indicated height of previously deposited material.

In US-A-6,311,099 an apparatus for regulating laser welding parameters is suggested that uses optical signals from the interaction zone. In this patent the optical signal is generated by near infrared radiation originating from the weld pool. The radiation is detected by a CCD camera and processed in order to obtain information about the physical dimensions of the melt pool.

SUMMARY OF THE INVENTION

The object of the present invention is to provide a advanced method for controlled deposition or remelting of material on substrates avoiding hot tearing defects, the columnar to equiaxed transition (CET) and melt pool convection. With material it should be possible to deposit material on single crystal substrates epitaxial with the base material or to transform a previously polycrystalline surface layer into single crystal material.

According to claim 1 a method was found of remelting of the surface of an article and according to claim 2 a second method was found of laser metal forming on the surface of an article.

The method can be used for remelting substrate material in order to re-establish a single crystal microstructure in the surface zones of the substrate, to transform a previously polycrystalline surface layer into single crystal material, to coat single crystal articles with a single crystal coating or for the repair of single crystal turbine components. Due to matched thermo-physical properties of solidified and base material the method leads to reduced stress and therefore to greater lifetime of the components.

With the online monitoring system and using automatic feed-back control of at least one process parameter such as laser power it is possible to establish and maintain optimum process conditions. In this favorable case the columnar to equiaxed transition (CET) and melt pool convection are avoided and a temperature field is created in the melt pool which leads to defect-free, epitaxial growth of the deposited material. Thus, it is possible to add new material without creation of grain boundaries. Beside the laser power process parameters like the relative speed between laser beam and the substrate, the carrier gas flow and mass feed rate of added material can be controlled.

Preferably as light source a fibre coupled high power diode laser is used. The inventive method combines laser power delivery, material supply and process monitoring in a dedicated laser/powder head. With this device the powder injection can be concentric with respect to the cone of captured optical signals from the melt pool or the cone of captured optical signals from the melt pool concentric with respect to the light source focussing cone. With the help of a dichroitic mirror infrared (IR) radiation from the melt pool is collected through the same optics which is used for laser focussing. The dichroitic mirror transmits laser light and reflects process light or vice versa.

The process signal from the melt pool can be coupled to a pyrometer or another fiber-coupled detector. For this purpose the optical properties of the monitoring system are chosen such that the measurement spot is smaller than the melt pool and located at the center of the melt pool. In a preferred embodiment according to the invention the optical signal is captured from the center and vicinity of the laser focal spot using a single optical fiber, an imaging fiber bundle or a charged coupled device (CCD) camera that is equipped with suitable optical filters. This information is used to determine the temperature a single spot or simultaneously at several locations in the center and in the vicinity of the melt pool. In a second case temperature gradients in the laser interaction zone can be analyzed.

The online feed back control of the laser power is decoupled from the main process control by means of a separate microprocessor. This allows faster parallel processing in real-time, i.e. independent from the operating system.

In another embodiment post-processing of the optical signal from the melt pool is used for quality control: The analysis of the measured data allows to optimize process parameters such that a desired microstructure is obtained. Recording of monitoring signals serves also for documentation purposes and for ensuring consistent product quality.

Moreover, dedicated commercially available software tools with enhanced functionality can be used for the realisation of the control system. As a consequence short loop times and advanced PID control features such as gain scheduling can be realised.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention are illustrated in the accompanying drawings, in which

Fig. 1 illustrates a gas turbine blade,

Fig. 2 illustrates an apparatus for carrying out the invention the present invention,

Fig. 3 illustrates an overall control system for carrying out the invention,

Fig. 4 illustrates an example of the invention and

Fig. 5 illustrates a second example of the invention.

The drawings show only the parts important for the invention. Same elements will be numbered in the same way in different drawings.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 shows a single crystal (SX) or directionally solidified (DS) article 1 such as blades or vanes of gas turbine engines, the gas turbine blade com-

prising a root portion 2, a platform 3 and a blade 4 and having a surface 5. The article 1 can as an example be made from a nickel or cobalt based super alloy. Investment casting methods for producing such SX or DS articles are known e.g. from the prior art US-A-4,96,501, US-A-3,690,367 or EP-A1-0 749 790. These articles 1 are normally made from a nickel or cobalt base super alloy.

The herein disclosed method can be used for remelting substrate material of the article 1 in order to re-establish a single crystal (SX) microstructure in the surface zones of the substrate or to transform a previously polycrystalline surface layer into SX material. In addition this method can be used for SX-coating application on SX-articles 1 or for the repair of single crystal (SX) turbine components. The underlying single crystal bulk material will act as a crystal seed for the remolten material. Due to matched thermo-physical properties the method leads to reduced stress and therefore to greater lifetime of the components.

It can be seen from the previous paragraph that high thermal gradients with the melt pool 7 are crucial for single crystal solidification. For this reason high power lasers such as CO_2, (fibre coupled) Nd-YAG or (fibre coupled) high power diode lasers offer a particularly attractive choice as a light source. Laser radiation can be focussed to small spots and generate thermal gradients in excess of 10^6 K/m. It is beneficial if the laser intensity is uniform over the heated area, which can be achieved by fiberoptic beam delivery. As laser power is very easily controlled, it is ensured that the criterion for single crystal solidification is maintained during the whole operation.

If during this operation the ratio G^n/V_s (where G is the temperature gradient in the melt pool, n is a material constant and V_s is the solidification speed) is kept above a material dependent threshold value, the subsequent solidification will occur epitaxially, i.e. without creating new grain boundaries.

In a typical application the laser will be focussed to a spot size of 1-3 mm diameter. Preferably the laser would be either of the Nd-YAG or high power

diode laser type. These lasers operate in the near infrared and about 30-40 % of the incident radiation is absorbed by typical super alloys. The laser beam will move at relatively slow speeds (approx. 1-10 mm/s) over the affected zones and operate in the conduction welding mode. Laser intensities of $1*10^3$ W/cm^2 to $5*10^4$ W/cm^2 will remelt a zone reaching up to 500µm below the surface. Larger penetration depths can be achieved by further reducing the processing speed or by preheating the article 1 prior to the melting of the surface 5 to a desired temperature in the range of 500 – 1000°C, e.g. with a high frequency generator. On preheated articles, however, thermal gradients are smaller and it is more difficult to meet the G^n/V_s criterion. On the other hand the risk of hot tearing defects during the whole operation is reduced.

Fig. 2 shows as an example an apparatus for controlled laser metal forming on the surface 5 of the article 1 according to the present invention. A laser beam 6 is moved over the surface 5 of the article 1 (or the article 1 is moved relative to the laser beam) thereby locally melting the surface 5 to form a melt pool 7. For coating or other laser metal forming applications material in the form of jet of powder 8 with a carrier gas 9 by means of a feeder 10 or a wire is added to the melt pool 7. From the melt pool 7 an optical signal 13 is continuously captured and used for the determination of the temperature, the temperature fluctuations and existing temperature gradients as properties of the melt pool 7. In one embodiment as seen in Fig. 2 the powder 8 injection can be concentric with respect to the cone of captured optical signals 13 from the melt pool 7.

As seen from the Fig. 3, the information of the optical signal 13 is used in a feedback circuit within a control system 16 to adjust process parameter such as the laser power by means of a controller 19, the relative speed between the laser beam 6 and the substrate, the flow rate of the carrier gas 9 and the mass feed rate of the injected powder 8 by means of a controller 18 in a way that desired melt pool 7 properties are obtained. For the method of remelting of the surface 5 of the article one or a combination of the process parameters laser power and/or the relative speed between the laser beam 6 and the arti-

cle 1 is used. Subsequently the melt pool 7 solidifies as indicated in Fig. 2 with reference number 12.

The method uses a combination of a concentric feeder 10, a fiber coupled laser and an on-line monitoring system with real time capability. With the help of the online monitoring system optimum process conditions are established and maintained where the columnar to equiaxed transition (CET) and melt pool convection are avoided. Hence, defect-free, epitaxial growth of the deposited material is observed. It is thus possible to add new material without creation of grain boundaries.

The new method combines laser power delivery, material supply and process monitoring in a dedicated laser/powder head as shown in Fig. 2. With the help of a dichroitic mirror 14 infrared (IR) radiation from the melt pool 7 is collected through the same optics which is used for laser focussing. The dichroitic mirror 14 transmits laser light and reflects process light of the optical signal 13 or vice versa.

The optical signal 13 from the melt pool 7 is coupled to a pyrometer 15 or another fiber-coupled detector which allows the online determination of the melt pool temperature. For this purpose the optical properties of the monitoring system are chosen such that the measurement spot is smaller than the melt pool and located at the center of the melt pool 7. In another embodiment according to the invention the optical signal 13 is captured from the center and vicinity of the laser focal spot using an imaging fibre bundle or a charged coupled device (CCD) camera that is equipped with suitable optical filters. This information is used to determine the temperature a single spot or simultaneously at several locations in the center and in the vicinity of the melt pool. In a second case temperature gradients in the laser interaction zone can be analysed.

The cone of captured optical signals 13 from the melt pool 7 can be concentric with respect to the laser focussing cone. The symmetry of this arrangement ensures that laser-powder interaction does not change during movements on

complex shaped components. This leads to consistent high quality of the process.

Fig. 3 shows the overall control system 16 for carrying out the invention. Besides a main process control 16 a controller 18 for controlling the feeder 10 and the whole apparatus and a controller 19 for controlling the laser is provided. The temperature information is used for the adjustment of process parameters such as the laser power, the relative speed between the laser beam 6 and the article 1, the feed rate of the injected powder 8 with the carrier gas 9 or an injected wire. For the method of remelting of the surface 5 of the article only one or a combination of the process parameters laser power and/or the relative speed between the laser beam 6 and the article 1 is used. This automatic feed-back control of the laser power by means of the controller 19 allows to establish a temperature field which is favourable for epitaxial growth. Moreover, the monitored optical signal 13 from the melt pool 7 allows to detect the onset of marangoni convection. Avoiding marangoni convection in the melt pool 7 will reduce the risk of hot tearing defects during solidification of the molten material.

As seen in Fig. 3, the online feed back controller 19 of the laser power is decoupled from the main process control 17 by means of a separate microprocessor. This allows faster parallel processing in real-time, i.e. independent from the operating system.

In another embodiment postprocessing of the optical signal 13 from the melt pool 7 is used for quality control: The analysis of the measured data allows to optimize process parameters such that a desired microstructure is obtained. Recording of monitoring signals serves also for documentation purposes and for ensuring consistent product quality.

Moreover, dedicated commercially available software tools (e.g. LabView RT) with enhanced functionality can be used for the realisation of the control system 16. As a consequence loop times <10 ms and advanced PID control

features such as gain scheduling, which means the use of different sets of PID parameters in predefined temperature intervals can be realised.

Example of the invention

As an example of the invention as shown in Fig. 4 a 300 μm polycristalline surface layer (of plasma sprayed coating material) was remelted and transformed into an epitaxially solidified surface layer. The matched orientation of the (fine) dendrites in the remolten area can be seen. Laser parameters were: P=220 W, v=1 mm/s, spot diameter: 2.5 mm.

A second example of the invention is shown in Fig. 5, where a 550 μm SX protection layer is deposited on a part made of SX turbine material. A subsequent re-melting step re-melts the surface layer of the deposit and leads to a very smooth surface finish and improved quality of the microstructure. In this case process parameters were: P=270 W, v=2 mm/s, powder feed rate: 2.4 g/min, laser spot diameter 1.8 mm for the deposition step and P=240 W, v=4 mm/s, laser spot diameter: 2.5 mm for the subsequent re-melting step.

REFERENCE NUMBERS

1	Article, e.g. blades or vanes for gas turbines
2	Root portion
3	Platform
4	Blade
5	Surface of article 1
6	Laser beam
7	Melt pool
8	Powder
9	Carrier gas
10	Feeder
11	Direction of movement
12	Solidified material
13	Optical signal
14	Dichroitic mirror
15	Pyrometer
16	Control system
17	Main process control
18	Controller for feeder 9
19	Controller for laser

CLAIMS

1. A method for controlled remelting of the surface (5) of an article (1), the method comprising the steps of
   (a) moving a light source and a signal capturing apparatus and the article (1) relative to each other, thereby
   (b) melting locally the surface (5) of the article (1) using the light source with a specific power for forming a melt pool (7),
   (c) capturing an optical signal (13) from the melt pool (7) using the signal capturing apparatus,
   (d) using the monitored optical signal (13) for the determination of temperature and temperature fluctuations as properties of the melt pool (7),
   (e) using the information of the temperature and temperature fluctuations of the melt pool (7) from the optical signal (13) within a control system (16) in a feedback circuit to adjust as process parameters the laser power and/or the relative speed of the light source to article (1) such that desired melt pool properties are obtained and subsequently
   (f) solidifying the melt pool (7).

2. A method for controlled laser metal forming on the surface (5) of an article (1), the method comprising the steps of
   (a) moving a light source and a signal capturing apparatus and the article (1) relative to each other, thereby
   (b) melting locally the surface (5) of the article (1) using the light source with a specific power for forming a melt pool (7),
   (c) injecting powder (8) with a carrier gas (9) or a wire into the melt pool (7).
   (d) capturing an optical signal (13) from the melt pool (7) using the signal capturing apparatus,
   (e) using the monitored optical signal (13) for the determination of temperature and temperature fluctuations as properties of the melt pool (7),
   (f) using the information of the temperature and temperature fluctuations of the melt pool (7) from the optical signal (13) within a control system (16) in a feedback circuit to adjust as process parameters one or a

combination of the power of the light source, the relative speed between the light source and the article (1), the mass feed rate of the added material and/or of the carrier gas (9) such that desired melt pool properties are obtained and subsequently

(g) solidifying the melt pool (7).

3. The method of claim 1 or 2, comprising the step of adjusting the process parameters such that melt pool properties are obtained to avoid columnar to equiaxed transition (CET) during solidification of the melt pool (7).

4. The method of claim 1 or 2, comprising the step of adjusting the process parameters such that melt pool properties are obtained to avoid convection in the melt pool (7).

5. The method of claim 2, wherein the article (1) consists of single-crystal (SX) or directionally solidified (DS) microstructure comprising the step of adjusting the melt pool properties to obtain epitaxial material build-up with thermo-physical properties of the deposit matched to those of the article (1).

6. The method of claim 1 or 2, wherein the surface (5) of the article (1) is remelted in order to re-establish a single crystal (SX) microstructure or to transform a polycrystalline surface layer into a single crystal (SX) structure.

7. The method of claim 1 or 2, wherein the light source is moved in respect to the article (1) or the article (1) is moved in respect to the light source.

8. The method of claim 1 or 2, wherein the light source power control is handled by a controller (19) with a different processor than that used for main process control (17) within the control system (16).

9. The method of claim 8, comprising the step of operating the light source power controller (19) in real time.

10. The method of claim 1 or 2, wherein gain scheduling is used for predefining PID control parameters within the control system (16).

11. The method of claim 1 or 2, wherein post-processing of the optical signal (13) from the molten (7) pool is used for quality control purposes, optimization of process parameters and/or process documentation.

12. The method of claim 1 or 2, wherein the captured optical signal (13) from the melt pool (7) is directed to a pyrometer (15).

13. The method of claim 12, comprising the step of capturing the optical signal (12) from a region in the center of the melt pool (7), whereby the pyrometer (15) measurement spot is smaller than the light source spot.

14. The method of claim 1 or 2, comprising the step of capturing the optical signal (13) by a fiber-coupled detector.

15. The method of claim 1 or 2, comprising further the steps of
    (b) capturing an optical signal (13) from the centre and vicinity of the light source focal spot,
    (c) using an optical fiber or an imaging fibre bundle or a CCD camera to capture the optical signal (13),
    (d) using the optical signal (13) to determine the temperature at several locations in the center and in the vicinity of the melt pool (7) and
    (e) using the information to determine temperature gradients in the light source interaction zone.

16. The method of claim 2, wherein the powder (8) injection is concentric with respect to the cone of captured optical signals (13) from the melt pool (7).

17. The method of claim 1 or 2, wherein the cone of captured optical signals (13) from the melt pool (7) is concentric with respect to the light source focussing cone.

18. The method of claim 1 or 2, comprising the step of using a dichroitic mirror (14) that transmits light from the light source and reflects light of the optical signal (13) or vice versa.

19. The method of claim 1 or 2, comprising the step of using a fibre coupled high power diode laser as light source.

20. The method according to any of the claims 1 to 20, wherein the article (1) is a gas turbine component made from a nickel or cobalt base super alloy.

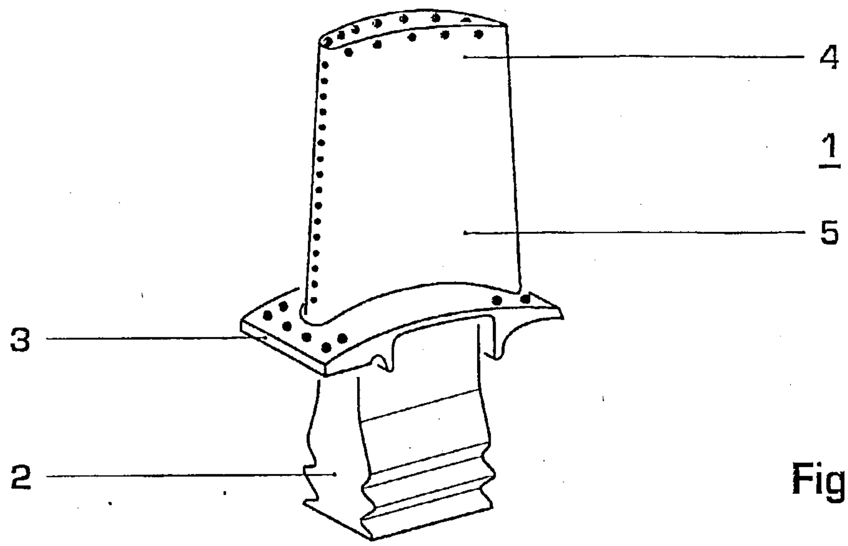

Fig. 1

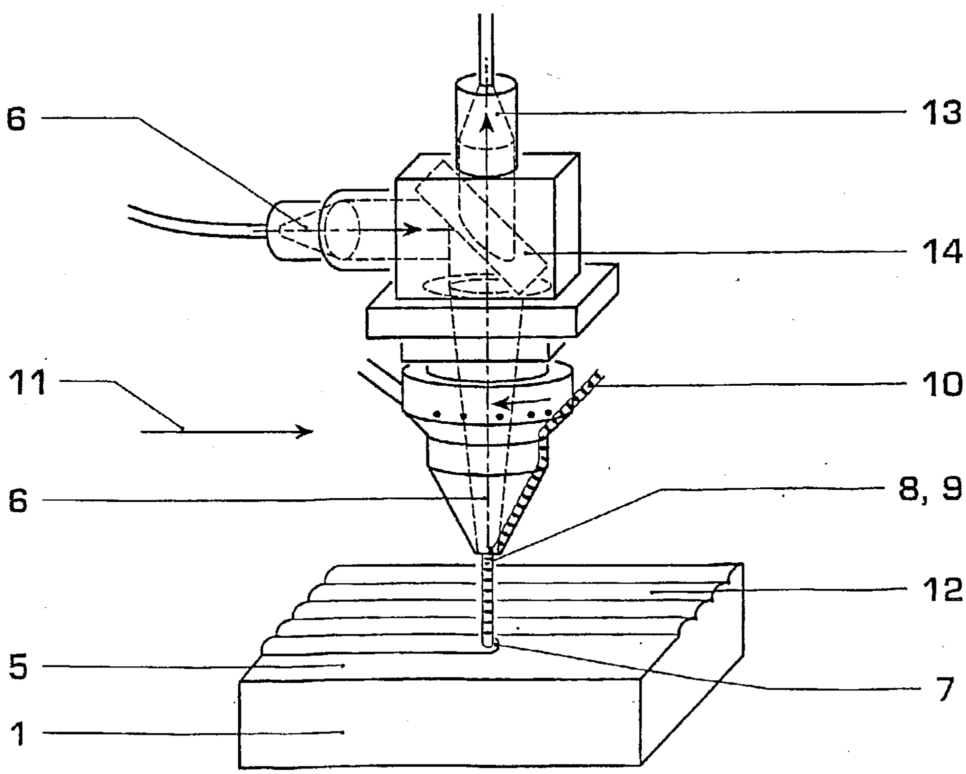

Fig. 2

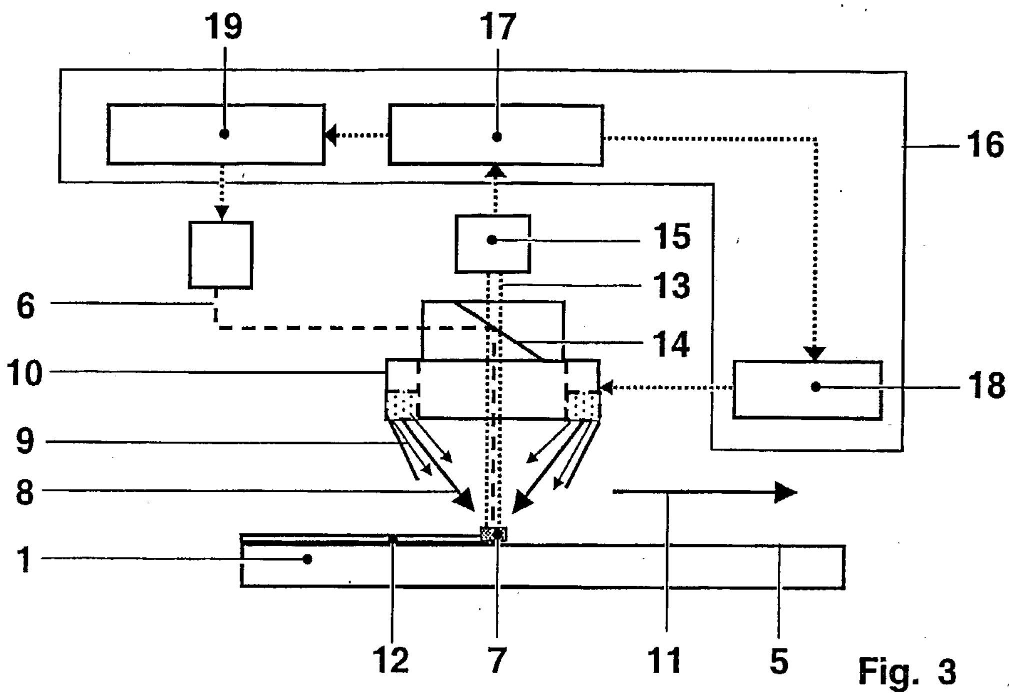

Fig. 3

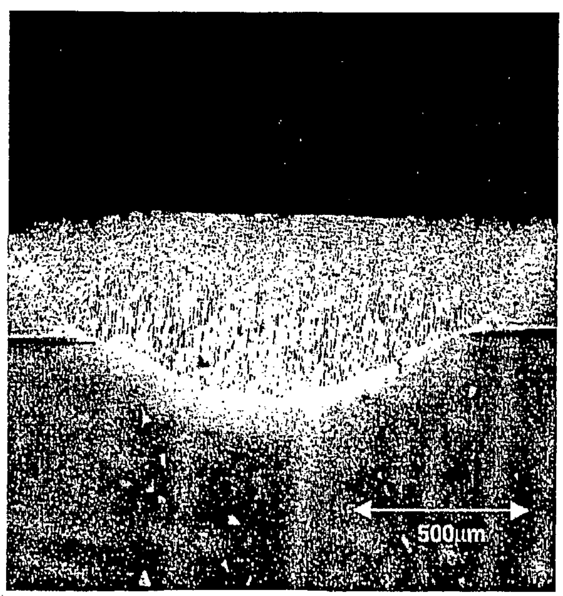

Fig. 4

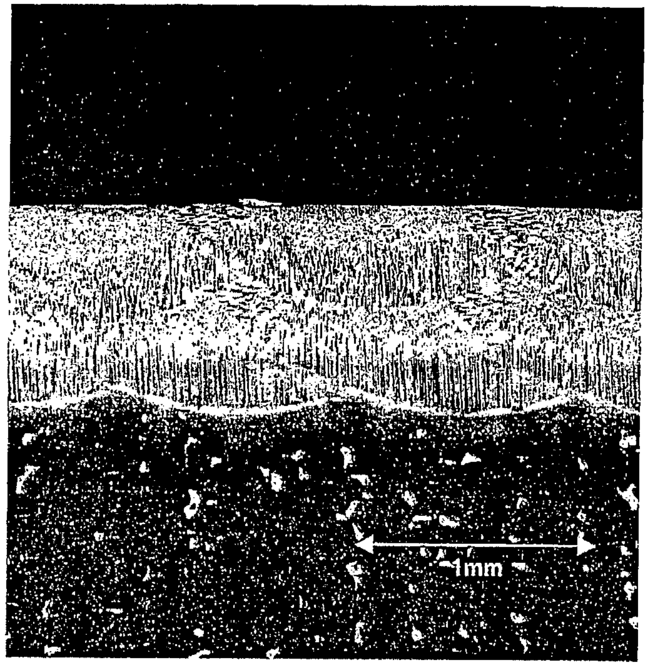

Fig. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CH 03/00098

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B23K26/03 B23K26/34 F01D5/00 F01D5/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B23K F01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 046 426 A (F.P. JEANTETTE ET AL) 4 April 2000 (2000-04-04) column 1, line 9 -column 2, line 8 column 5, line 1-21 column 8, line 8-27 column 10, line 1-49; figure 9	2,4,7,9, 11,12,16
X	DE 198 53 733 C (FRAUNHOFER GES FORSCHUNG) 24 February 2000 (2000-02-24)	1,7,9, 12,13,18
Y	the whole document	2-6,20
Y	US 6 024 792 A (KURZ WILFRIED ET AL) 15 February 2000 (2000-02-15) cited in the application the whole document	2-6,20

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
10 April 2003	29/04/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Jeggy, T

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